Industrial Solutions
The STAR process® by Uhde
The Business Area Industrial Solutions of thyssenkrupp is a world leader for planning, construction and service in the field of industrial plants and systems. Together with our customers we develop solutions at the highest level and deliver efficiency, reliability and sustainability throughout the entire life cycle. Our global network, with around 19,000 employees at 70 locations, enables us to provide turnkey solutions worldwide which set new benchmarks with their high productivity and particularly resource conserving technologies.

We are at home in many different industries. Along with chemical, fertilizer, coking, refinery, cement and other industrial plants, our portfolio also includes equipment for open-cast mining, ore processing and transshipment, as well as associated services. In the naval sector, we are a leading global system supplier for submarines and surface vessels. As an important system partner to our customers in the automotive, aerospace and battery industries, we optimize the value chain and improve performance.
<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>04</td>
<td>Introduction</td>
</tr>
<tr>
<td>06</td>
<td>Steam reforming and olefin production plants supplied by Uhde</td>
</tr>
<tr>
<td>07</td>
<td>- Steam reforming</td>
</tr>
<tr>
<td></td>
<td>- Olefins</td>
</tr>
<tr>
<td>08</td>
<td>Dehydrogenation – basic principles</td>
</tr>
<tr>
<td></td>
<td>- Conventional Dehydrogenation</td>
</tr>
<tr>
<td></td>
<td>- Oxydehydrogenation</td>
</tr>
<tr>
<td>09</td>
<td>STAR process® technology</td>
</tr>
<tr>
<td></td>
<td>- Reaction Section</td>
</tr>
<tr>
<td></td>
<td>- STAR catalyst®</td>
</tr>
<tr>
<td></td>
<td>- Process pressure</td>
</tr>
<tr>
<td></td>
<td>- Operating cycle</td>
</tr>
<tr>
<td>10</td>
<td>- Space-Time-Yield</td>
</tr>
<tr>
<td></td>
<td>- Heat recovery</td>
</tr>
<tr>
<td></td>
<td>- Gas separation</td>
</tr>
<tr>
<td></td>
<td>- Fractionation</td>
</tr>
<tr>
<td>13</td>
<td>- STAR process® reformer</td>
</tr>
<tr>
<td>14</td>
<td>- STAR process® oxyreactor (optional)</td>
</tr>
<tr>
<td>16</td>
<td>Comparison of dehydrogenation technologies</td>
</tr>
<tr>
<td></td>
<td>- General remarks</td>
</tr>
<tr>
<td></td>
<td>- Adiabatic reactors connected in series</td>
</tr>
<tr>
<td>17</td>
<td>- Parallel adiabatic reactors</td>
</tr>
<tr>
<td></td>
<td>- STAR process®</td>
</tr>
<tr>
<td></td>
<td>- STAR process® with oxydehydrogenation</td>
</tr>
<tr>
<td>18</td>
<td>Application of the STAR process®</td>
</tr>
<tr>
<td></td>
<td>- Dehydrogenation of propane to propylene</td>
</tr>
<tr>
<td></td>
<td>- Dehydrogenation of butanes</td>
</tr>
<tr>
<td>19</td>
<td>- Dehydrogenation for the production of alkylate</td>
</tr>
<tr>
<td>21</td>
<td>- Dehydrogenation for the production of dimers</td>
</tr>
<tr>
<td>23</td>
<td>Services for our customers</td>
</tr>
</tbody>
</table>
Introduction

Medium and long-term forecasts expect to see a growing demand for on-purpose technologies for olefin production (e.g. propylene, butylenes) such as dehydrogenation of light paraffins.

Today most propylene is produced as co-product in steam crackers (approx. 50%) and as by-product in FCC units (approx. 30%). Approx. 20% is produced by on-purpose technologies like propane dehydrogenation (PDH) or metathesis.

The annual growth rates expected for propylene are higher than those for ethylene. In addition, ethane feedstocks are increasingly used in steam crackers because of their more favorable economics compared to naphtha or LPG feedstocks. Because ethane cracking yields considerably less propylene than LPG or naphtha cracking this will result in a supply gap for supply of propylene. This gap can very economically be filled by propane dehydrogenation applying the STAR process®.

Rapid further growth is expected for on-purpose propylene and butylene production to yield the following derivatives:

<table>
<thead>
<tr>
<th>Derivatives of Propylene</th>
<th>Derivatives of Isobutylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene*</td>
<td>MTBE/ETBE</td>
</tr>
<tr>
<td>Propylene Oxide**</td>
<td>Alkylate</td>
</tr>
<tr>
<td>Cumene</td>
<td>Dimers</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>MMA</td>
</tr>
<tr>
<td>Acrylic Acid</td>
<td>Alcohols/MEK</td>
</tr>
<tr>
<td>Oxo-Alcohols</td>
<td>Butyl Rubber</td>
</tr>
</tbody>
</table>

*Authorized Contractor **Own technology with Evonik

The STAR process®, STAR being the acronym for STeam Active Reforming, is a commercially established dehydrogenation technology that was initially developed by Phillips Petroleum Company, Bartlesville, OK, USA.

thyssenkrupp Industrial Solutions acquired the technology including process know-how and all patents related to process and catalyst from Phillips in December 1999.
Two commercial units applying the STAR process® technology have been commissioned for the integrated production of isobutane and MTBE:

- Coastal Chemical Inc., Cheyenne, WY, USA, was commissioned in 1992 and produces 100,000 t/year of isobutene.
- Polybutenos, Argentina, was designed for a capacity of 40,000 t/year of isobutene and was commissioned in 1994.

In 2006 thyssenkrupp Industrial Solutions was awarded a lump sum turnkey contract to build a 350,000 t/year PDH/PP complex by Egyptian Propylene & Polypropylene Company (EPP) in Port Said, Egypt.

In 2009 and 2010 other clients have awarded thyssenkrupp Industrial Solutions contracts for plants with an overall capacity of 450,000 t/year.

Within the framework of the olefin expansion project of Formosa Plastics Corporation in Point Comfort, USA, thyssenkrupp Industrial Solutions has been awarded a contract for an even larger PDH plant with a capacity of 545,000 t/year.
Steam reforming and olefin production plants supplied by thyssenkrupp Industrial Solutions
Steam reforming
The references for steam reforming attached hereto reflect our experience in the fields of reaction sections and steam generation equipment applied in the STAR process®. Today the total count is as follows:

- **Steam reformer**: more than 70 units (basis for STAR process® reformer)
- **Secondary reformer**: more than 40 units (basis for STAR process® oxyreactor)

Olefins
thyssenkrupp Industrial Solutions has also designed and successfully commissioned plants for a wide range of applications for the production of olefins and olefin derivatives using the technologies described in Table 1. By combining them with the STAR process® thyssenkrupp Industrial Solutions is in the position to offer complete process routes:

- Production of polypropylene (PP) or propylene oxide (PO) from propane.
- Production of MTBE or other high octane blend-stocks (e.g. alkylate or dimers) from butane.

Another advantage of the STAR process® is that thyssenkrupp Industrial Solutions combines the functions of technology owner/licensor and EPC contractor and is therefore able to provide process performance guarantees as well as total plant completion and mechanical guarantees within the framework of a single-point responsibility (turnkey) contract.

<table>
<thead>
<tr>
<th>Product</th>
<th>Process Licensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene dichloride</td>
<td>Vinnolit</td>
</tr>
<tr>
<td>Ethylene oxide</td>
<td>Shell Chemicals</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>Shell Chemicals</td>
</tr>
<tr>
<td>Propylene oxide</td>
<td>Evonik-thyssenkrupp Industrial Solutions</td>
</tr>
<tr>
<td>High density polyethylene</td>
<td>LyondellBasell</td>
</tr>
<tr>
<td>Low density polyethylene</td>
<td>LyondellBasell</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>LyondellBasell</td>
</tr>
<tr>
<td>Alkylate</td>
<td>Du Pont, ConocoPhillips, UOP</td>
</tr>
<tr>
<td>MTBE/ETBE</td>
<td>thyssenkrupp Industrial Solutions</td>
</tr>
<tr>
<td>Dimers</td>
<td>Axens, UOP</td>
</tr>
<tr>
<td>Olefins</td>
<td>thyssenkrupp Industrial Solutions</td>
</tr>
</tbody>
</table>

Table 1: Our technology portfolio for the production of olefins and olefin derivatives
Dehydrogenation – basic principles

Conventional Dehydrogenation
Dehydrogenation is an endothermic equilibrium reaction. The conversion rate of paraffins increases with decreasing pressure and increasing temperature. In general the process temperature will increase with decreasing carbon number to maintain conversion at a given pressure. As shown below for propane and butane, respectively, the main reaction is the conversion of paraffin to olefin.

Propane dehydrogenation (PDH):
\[ \text{C}_3\text{H}_8 \rightleftharpoons \text{C}_3\text{H}_6 + \text{H}_2 \]

Butane dehydrogenation (BDH):
\[ \text{C}_4\text{H}_{10} \rightleftharpoons \text{C}_4\text{H}_8 + \text{H}_2 \]

Lower hydrocarbons (i.e. lower in carbon number than the feedstock) are also formed. One of the side reactions that occur is cracking, which is primarily thermal and results in the formation of small amounts of coke.

Oxydehydrogenation
Obviously the conversion rate is limited by the thermodynamic equilibrium for a given pressure and temperature. As conversion approaches equilibrium, reaction velocity decreases and catalyst activity is not fully utilised. However, if oxygen is introduced into the system it will form \( \text{H}_2\text{O} \) with part of the hydrogen shifting the equilibrium of the dehydrogenation reaction towards increased conversion. Figure 1 shows the influence of oxygen addition which shifts the equilibrium towards increased conversion of propane to propylene. The formation of \( \text{H}_2\text{O} \) is an exothermic reaction which provides the heat of reaction for further endothermic conversion of paraffins to olefins.

![Figure 1: Thermodynamic equilibrium data (Partial pressure 1 bar, molar oxygen to propane ratios)](image)
STAR process® technology

**Reaction Section**
The reaction section comprises an externally heated reactor (STAR process® reformer) including a highly efficient heat recovery system for feed preheating and steam generation. Optionally, the reaction section is equipped with an oxyreactor to increase conversion rates.

**STAR catalyst®**
The STAR catalyst® is based on a zinc and calcium aluminate support that, impregnated with various metals, demonstrates excellent dehydrogenation properties with very high selectivities at near equilibrium conversion rates. Due to its basic nature it is also extremely stable in the presence of steam and oxygen at high temperatures. This commercially proven noble metal promoted catalyst in solid particulate form is used in the STAR process®.

**Process pressure**
The reaction takes place in the presence of steam, which reduces the partial pressure of the reactants. This is favourable, as the endothermic conversion of paraffin to olefin increases with decreasing partial pressures of hydrocarbons. Competing dehydrogenation technologies operate at reactor pressures slightly above atmospheric pressure or even under vacuum. In the STAR process®, however, the reactor outlet pressure is significantly above atmospheric pressure. This results in a sufficient pressure drop allowing to efficiently utilise the heat available in the reactor effluent and to design the raw gas compressor with a higher suction pressure than competing technologies, thus saving investment and operating costs.

**Operating cycle**
During normal operation a minor amount of coke is deposited on the catalyst which requires frequent regeneration. Steam present in the system converts most of the deposited coke to carbon dioxide. This leaves very little coke to be burnt off during the oxidative regeneration, extending operating cycles and ensuring quick and simple regeneration. Also no additional treatment is required for coke suppression or catalyst reactivation (e.g. sulfiding or chlorinating). The cycle length is seven hours of normal operation followed by a regeneration period of one hour. Therefore only 14.7% additional reactor capacity is needed to account for regeneration requirements, which is the lowest of all commercial technologies.
Space-Time-Yield
The STAR process® offers a higher space-time yield than competing technologies because of significantly higher reaction velocities in the reactors. This results in a very compact reactor design. If combined with an oxyreactor, the space-time yield is even higher.

• The higher yield reduces the dry gas flow to the raw gas compressor and to the down-stream units for product treatment.
• These advantages result in lower investment and utility consumption.

Heat recovery
Heat from the process gas is efficiently recovered and utilised for:
• Feed vaporisation and superheating
• Direct heating of fractionation column reboilers
• Generation of refrigerant

Gas separation
Product quality is ensured by a steady continuous feed of constant composition to the fractionation unit. The gas separation unit is designed to meet these requirements.

The main features of this design are as follows:
• The cold box removes all light ends, including hydrogen from the reactor product.
• Only approx. 10% of the propane/propylene mixture enter the cold box so that in case of a cold box failure a production rate of approx. 90% can still be achieved, which is a unique feature of the STAR process®.
• Very low olefin losses as > 99% of the olefin produced in the reactor are recovered.

Fractionation
The main features of the fractionation are:
• No gas phase is admitted to the fractionation. The entire fractionation feed is liquid, which is collected in an intermediate storage vessel, from where it is continuously fed to the distillation columns. Hence the operation of this section is not influenced by the load variations (between the normal and regeneration mode) at the front end.

• Light ends are removed as tail gas.
Figure 3:
STAR process® reformer connected in series with an oxyreactor (optional)
Figure 4: Furnace box of top-fired Uhde STAR process® reformer
STAR process® reformer

The STAR process® reformer is an industrially well known and commercially established top fired “steam reformer” of the tubular fixed bed type not susceptible to catalyst losses due to attrition.

The main features of the reformer are:

- Top firing for optimum uniformity of tube skin temperature profile.
- Internally insulated cold transfer line made from carbon steel and located externally under the reformer bottom.
- Each tube row connected to a separate hot outlet manifold.
- Each hot outlet manifold line is connected to a main cold transfer line.

Since 1966 thyssenkrupp Industrial Solutions has installed more than 70 reformer units of this type in various parts of the world to generate synthesis gas for the production of ammonia, methanol, oxo alcohols and hydrogen.

As shown in table 2 the operating conditions for the above mentioned applications are far more stringent than those required for dehydrogenation.

The top fired reformer design ensures a uniform temperature profile with a steady increase of temperature in the catalyst bed, thus efficiently utilising the activity of the catalyst.

The reformers of thyssenkrupp Industrial Solutions feature a very high availability of five years of operation between maintenance shutdowns.

Table 2:
Industrial applications of steam reformers

<table>
<thead>
<tr>
<th>Application</th>
<th>Pressure [bar a]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>40</td>
<td>780 - 820</td>
</tr>
<tr>
<td>Methanol</td>
<td>20 - 25</td>
<td>850 - 880</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>20 - 25</td>
<td>880</td>
</tr>
<tr>
<td>Oxogas</td>
<td>9 - 12</td>
<td>900</td>
</tr>
<tr>
<td>Olefins (STAR process®)</td>
<td>5 - 6</td>
<td>550 - 590</td>
</tr>
</tbody>
</table>
**STAR process® oxyreactor (optional)**

The adiabatic oxyreactor is a refractory lined vessel. The design of this item of equipment, as shown in figure 5, is virtually the same as that of the thyssenkrupp Industrial Solutions secondary reformer, used in ammonia plants. The only difference between them is how the oxidant is distributed. Air diluted with steam is distributed so as to allow the oxygen to come into contact with the process fluid at the top of the catalyst bed.

Compared to ammonia plants, the operating conditions of the oxydehydrogenation unit are much milder (refer to table 3).

<table>
<thead>
<tr>
<th>Service</th>
<th>Ammonia</th>
<th>Olefins (STAR process®)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure (bar abs.)</td>
<td>38</td>
<td>max. 6</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>970</td>
<td>max. 700</td>
</tr>
</tbody>
</table>

Table 3: Comparison of operating conditions of the secondary reformer for the production of ammonia synthesis gas and of the STAR process® oxyreactor for dehydrogenation

The following features highlight the safe and reliable design provided by thyssenkrupp Industrial Solutions:

- Reactor effluent from the STAR process® reformer enters the STAR process® oxyreactor at the bottom and passes into one centrally arranged tube, which conducts the gas to the top. This eliminates troublesome external hot piping to the head of the reactor.

- Process gas is discharged from the central tube into the dome for reversal of the flow direction.

- Oxygen is introduced into the system and uniformly distributed directly onto the catalyst surface via a proprietary oxygen distribution system so that process gas and oxygen are rapidly mixed and directly contacted with the catalyst bed to achieve high selectivities for the conversion of hydrogen with oxygen.

Figure 5: STAR process® oxyreactor design
Comparison of dehydrogenation technologies

The reaction section of the STAR process® with an oxydehydrogenation stage offers significant advantages over competing technologies, which will be explained below.

General remarks
Dehydrogenation is an endothermic equilibrium reaction. As more and more product is formed, the residence time required for producing a certain amount of product will continuously increase as the driving force decreases. This means, that the yield per time and catalyst volume (space-time-yield) will decrease as the dehydrogenation reaction progresses.

The following chapters describe the technologies available on the market.

The two most expensive units within a dehydrogenation plant are the reaction section and the raw gas compression section. Defining the reaction pressure will also define the required compression ratio for the raw gas compressor, which directly influences compressor operating and investment costs.

Adiabatic reactors connected in series
The endothermic reaction will cause a temperature drop across the catalyst bed so that the reactor feed needs to be preheated. Across the catalyst bed, the temperature profile and conversion rate are opposed.

Hence conversion is limited by the reactor outlet temperature which is lower than the inlet temperature.

This system, besides a charge heater, also requires preheating of partially reacted gases before entering the next reactor (Figure 6), which results in cracking of already formed olefin. So coke suppression measures must be taken in the intermediate heaters to prevent an increase of coke deposits on the catalyst which will temporarily deactivate it and result in a comparatively low space-time yield.

One of the measures to suppress coke formation is to recycle hydrogen. This is bound to decrease the driving force of the reaction as hydrogen is also a dehydrogenation product.
Parallel adiabatic reactors
Such systems require multiple parallel beds, particularly for large capacities. Ensuring efficient distribution of feed is bound to limit the diameter of the reactor. The allowable pressure drop will limit the bed height as well. Conversion takes place in one bed which will also limit the space velocity.

Typically, feed preheated does not supply sufficient heat for high conversion rates. This means that during the regeneration phase heat has to be introduced into the system which is utilised during the following reaction phase. Catalyst is used as a heat source for endothermic reaction. During the reaction phase the catalyst bed temperature decreases (Figure 7), which in turn leads to a short cycle length of less than 20 minutes. Hence several parallel beds at large capacities cannot be avoided. The space-time-yield is even lower than in adiabatic systems connected in series.

For world scale plants a large number of reactors connected in parallel is required. Only few of them are used at the same time for dehydrogenation. Switching from one reactor to the next requires many valves for hot operating service which is very costly.

STAR process® (conventional dehydrogenation)
External heating in the reformer ensures a steady temperature increase in the catalyst bed (Figure 8). This is in accordance with the thermodynamic requirements for an increased conversion rate.

The overall effect is a high space-time-yield at increased conversion and selectivity. The higher operating pressure reduces costs in the downstream compression unit.

STAR process® with oxydehydrogenation stage
This configuration with an externally heated tubular reactor (STAR process® reformer) followed by an air or oxygen operated adiabatic reactor (oxyreactor) combines the advantages of both reactor systems:

- STAR process® reformer, as known from the steam reforming process for the production of synthesis gas, monitors the temperature profile to efficiently utilise the activity of the catalyst.
- Feeding oxygen to the oxyreactor shifts the thermodynamic equilibrium and provides the heat of reaction required for further dehydrogenation (Figure 9).
- The space-time yield obtained is even higher than in the conventional STAR process®
Application of the STAR process®

Dehydrogenation of propane to propylene
Propylene is a base petrochemical used for the production of polypropylene (PP), oxo-alcohols, acrylonitrile, acrylic acid (AA), propylene oxide (PO), cumene and others.

About 60% of the propylene produced today is used as feedstock for the production of PP.

With the STAR process® thyssenkrupp Industrial Solutions can offer to its clients single point responsibility for complete process routes to propylene derivatives, e.g. PP or PO, based on on-purpose propylene production from propane. Process economics are very favourable for a production complex, e.g. of PP from propane by PDH (STAR process®) and subsequent polymerisation.

Hydrogen produced by dehydrogenation can be purified and used as feedstock for subsequent plants (e.g. for H₂O₂ production by means of the Evonik-Uhde HPPO process) minimising raw material costs.

The feed supplied to subsequent plants is free of contaminants (CO, CO₂, and sulphur compounds) as they are efficiently removed in the STAR process®. Thus, a Selective Hydrogenation Unit (SHU) or guard beds for removal of trace components are in most cases not required. In addition, recycle streams from the PP plant can be purified using the existing equipment of the PDH plant. Integration of utility and offsite units (steam, cooling water, refrigerant, oxygen/nitrogen, etc.) will further improve project economics.

The process configuration of a stand-alone propylene dehydrogenation plant is shown in figure 2, page 9.

Dehydrogenation of butanes
Dehydrogenation of isobutane to isobutene for the production of MTBE is a commercially well established process route. MTBE is phased out in the USA. However, it is not clear, whether this will apply to other regions as well.

Other options for octane boosting are alkylate and dimers. Dehydrogenation of butanes to butenes can also be used for the production of alkylate or dimers, which are used as blending stock to enhance the quality of unleaded gasoline to premium grade.

The world’s first commercial scale plant for the production of propylene oxide based on the innovative HPPO process has been in successful operation since 2008.
Dehydrogenation for the production of alkylate

Both HF and H₂SO₄ alkylation are mature and efficient technologies for the production of C₇ and C₈ alkylate from propene and butenes. C₈ alkylate has higher octane numbers than C₇ alkylate.

The Research Octane Number (RON) of the alkylate produced will depend on the type of olefin as well as on the process applied (refer to table 5). It is worthwhile to limit isobutene when the alkylation process is based on H₂SO₄, whereas preferable feed components for HF alkylation are butene-2 and isobutene. The plant configuration will depend on the alkylation scheme selected. For alkylation based on H₂SO₄ the preferred feedstock is mixed butanes.

The process steps are as follows:
- STAR process® oxydehydrogenation
- Butenex®
- Selective hydrogenation
- H₂SO₄ alkylation

Butenex®, a technology licensed by thyssenkrupp Industrial Solutions, is an extractive distillation process. The C₄ fraction from the STAR process is separated into butenes and butanes. A mixture of N-formylmorpholine (NFM) and morpholine is used as solvent. NFM is a commercially well established solvent known from its application in our Morphylane® process for the extractive distillation of aromatics. To date two commercial Butenex® units have been successfully designed and commissioned by us.

<table>
<thead>
<tr>
<th>Alkylate from</th>
<th>HF alkylation</th>
<th>H₂SO₄ alkylation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butene-1</td>
<td>91</td>
<td>98</td>
</tr>
<tr>
<td>Butene-2</td>
<td>97</td>
<td>98</td>
</tr>
<tr>
<td>Isobutene</td>
<td>95</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 4: RON of alkylate depending on alkylation technology and olefin used
Depending on the content of isobutane in the mixed butanes feed, the STAR process® unit could be conceived to include a deisobutaniser column so as to separate isobutane from n-butane in the mixed butanes feed. N-butane is recycled from the Butenex® unit to the STAR process® unit. Butadiene contained in the unsaturated C₄ stream (extract) from Butenex® is selectively hydrogenated to butene-1. The selectively hydrogenated stream is the olefin feed to alkylation.

It seems to be advantageous to process isobutane (instead of mixed butanes), if the selected process is HF alkylation.

The reasons are:

- The RON of C₈ alkylate derived from isobutene is high (95).

- For a given conversion rate the selectivity of isobutene (from isobutane) is higher than that of n-butenes (from n-butane), reducing the plant feed by 6%.

- Selective hydrogenation of butadiene will not be required.

- The STAR process® unit can be designed to provide an isobutane/isobutene mixture having the desired stochiometric ratio for alkylation. Thus no unconverted paraffin needs to be recycled to the STAR process unit and as a result no Butenex® unit is required.
Dehydrogenation for the production of dimers

The quantity and quality (RON) of gasoline produced will depend on whether isobutene is selectively dimerised or whether all butenes present in the feed are dimerised. When processing mixed butenes, the concentration of isobutene in mixed butenes will also influence the quality of gasoline.

Dimerisation of mixed butenes will result in a liquid product of which max. 80% is gasoline and 20% is jet fuel. The liquid product yield will be around 95 - 98% of the butenes present in feed. The octane rating will increase with the concentration of isobutene in the feed. An isobutene concentration of about 50% (in total butenes) will be required to obtain unleaded premium gasoline (RON 95).

Selective dimerisation of isobutene (in the mixed butenes feed) will result in a liquid product which will primarily consist of high octane gasoline (RON 99) and a small amount (4% of liquid product) of jet fuel. However, the liquid product yield is low. Whereas isobutene is virtually completely dimerised the conversion of n-butenes will be only in the order of 50%. Isobutene will be completely converted to high octane gasoline (RON 99).

The process configuration (Figure 14) includes the following process steps:

- STAR process®
- Selective hydrogenation of butadiene
- Dimerisation unit (incl. product hydrogenation)

The selective hydrogenation of butadiene is only required if the plant feed consists of mixed butanes.

Hydrogen required for selective hydrogenation of feed for dimerisation and for product hydrogenation will be supplied from the STAR process® unit. The utility system of the dimerisation and hydrogenation units is integrated into the STAR process® unit to enhance process economy. Unconverted butanes are recycled from the dimerisation unit to the STAR process® unit.

![Figure 12: Dimers from butanes](image-url)
Inside view of the furnace box of an Uhde steam reformer
thyssenkrupp Industrial Solutions is dedicated to providing its customers with a wide range of services and to supporting them in their efforts to succeed in their line of business.

With our worldwide network of subsidiaries, associated companies and experienced local representatives, as well as first-class backing from our head office, thyssenkrupp Industrial Solutions has the ideal qualifications to achieve this goal.

We place particular importance on interacting with our customers at an early stage to combine their ambition and expertise with our experience.

Whenever we can, we give potential customers the opportunity to visit operating plants and to personally evaluate such matters as process operability, maintenance and on-stream time. We aim to build our future business on the trust our customers place in us.

thyssenkrupp Industrial Solutions provides the entire spectrum of services of an EPC contractor, from the initial feasibility study, through financing concepts and project management right up to the commissioning of units and grass-roots plants.

Our impressive portfolio of services includes:

- Feasibility studies/technology selection
- Project management
- Arrangement of financing schemes
- Financial guidance based on an intimate knowledge of local laws, regulations and tax procedures
- Environmental impact studies
- Licensing incl. basic/detail engineering
- Utilities/offsites/infrastructure
- Procurement/inspection/transportation services
- Civil works and erection
- Commissioning
- Training of operating personnel using an operator training simulator
- Plant operation support/plant maintenance
- Remote Performance Management (Teleservice)

The policy of thyssenkrupp Industrial Solutions and its subsidiaries is to ensure utmost quality in the implementation of our projects. Our head office and subsidiaries worldwide work according to the same quality standard, certified according to DIN/ISO 9001/EN29001.

We remain in contact with our customers even after project completion. Partnering is our byword.

By organising and supporting technical symposia, we promote active communication between customers, licensors, partners, operators and our specialists. This enables our customers to benefit from the development of new technologies and the exchange of experience as well as troubleshooting information.

We like to cultivate our business relationships and learn more about the future goals of our customers. Our after-sales services include regular consultancy visits which keep the owner informed about the latest developments or revamping options.

thyssenkrupp Industrial Solutions stands for tailor-made concepts and international competence. For more information contact one of the thyssenkrupp Industrial Solutions offices near you or visit our website:

www.thyssenkrupp-industrial-solutions.com

Further information on this subject can be found in the following brochures:

- Ammonia
- Organic chemicals and polymers
- Propylene oxide